MONTHLY WEATHER REVIEW

Editor, EDGAR W. WOOLARD

Vol. 64, No. 8
W. B. No. 1189

AUGUST 1936

Closed October 3, 1936
Issued November 6, 1936

PHYSICAL FACTORS AFFECTING THE VISIBILITY OF SMALL SMOKE COLUMNS

By George M. Byram

[Formerly of the Pacific Northwest Forest Experiment Station, United States Forest Service, August 1935]

The investigations reported in this paper were made for the Pacific Northwest region (Washington and Oregon) of the United States Forest Service for the purpose of determining the maximum distance at which fire lookouts can be depended upon to discover the smoke of small fires; but the results obtained may be of value to anyone interested in the atmospheric conditions that affect visibility.

This report is confined to a consideration of a few of the physical factors that influence the visibility of small columns of smoke. These are:

1. Atmospheric conditions.
   a. Haze brightness.
   b. Lack of transparency of the air.
2. Intrinsic brightness of backgrounds.
3. Position of sun with respect to smoke columns.
4. Shadows from low sun in valleys and canyons in mountainous regions.
5. Cloudiness of the sky.
6. Size of smoke column.

The basic data were obtained by observing the maximum distances at which small columns of smoke could be seen under different combinations of these physical factors, and by taking simultaneous measurements of visibility conditions. A constant volume of smoke for the tests, similar in quantity and quality to the smoke from a small fire (approximately 200 square feet) in Douglas fir or ponderosa pine duff on a dry midsummer day, was produced by specially constructed smoke pots. Measurements of atmospheric conditions and of the intrinsic brightness of backgrounds were made with the visibility photometer and the haze meter.[1] Single columns of smoke were sent up on calm days at different distances from an observation point until the maximum distance at which the smoke column could be seen was found. In all cases the maximum-visibility distance reduced 30 percent was assumed to be the safe-visibility distance. Variations due to quality of observer's eyesight were eliminated by using only one observer (the writer) throughout the study. A mirror-signal system enabled the observer to know when and where to look for the smoke so that variations due to attention and ability to find the smokes were eliminated.

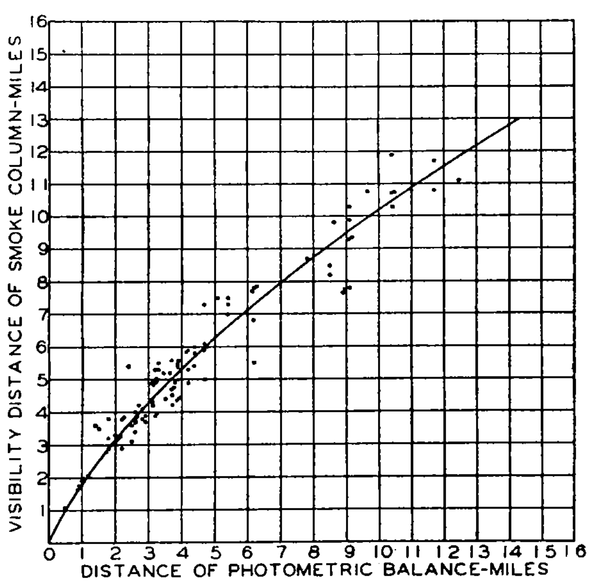

Figure 1.—Relation between the safe visibility distance of standard test smoke columns and the distance of photometric balance of the haze meter.

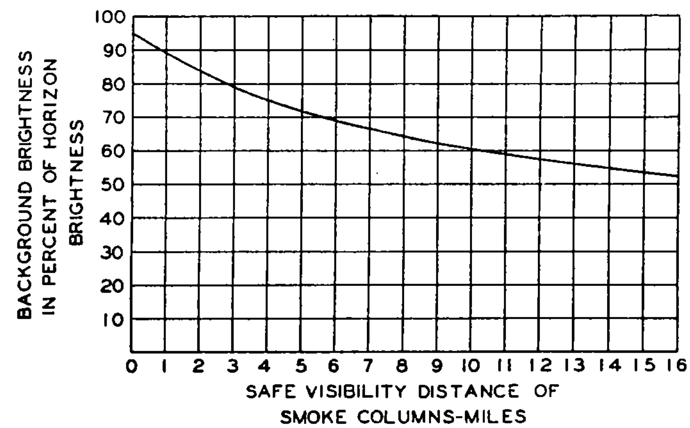

Figure 2.—Relation of the visibility distance of test smokes to the brightness of the background against which they are seen.

Figure 1 shows the maximum distance of safe visibility of the smoke columns against dark-timbered backgrounds plotted as a function of the distance of photometric balance as indicated by the lookout haze meter.[1] Such balance is obtained when the meter is directed at a spot on the landscape which is 60 percent as bright as the sky at the horizon in the same direction. If measurements are made against dark-timbered backgrounds, it is the distance which will reduce the intensity of a beam of light passing through this distance to 40 percent of its initial value.

Figure 2 shows the background brightness at the limit of safe visibility. Values for this curve were computed[2] from figure 1. The background brightness is expressed

[1] McArdle, Richard E., A Visibility Meter for Forest Fire Lookouts, Journal of Forestry, vol. XXXIII, April 1935.
Byram, Geo. M., Visibility Photometers for Measuring Atmospheric Transparency, Journal of the Optical Society of America, vol. XXV, pp. 388-392, December 1935.

[2] By methods developed in "Visibility Photometers for Measuring Atmospheric Transparency", previously cited.

as a percent or fraction of the horizon brightness in the same direction. This is necessary because the brightness of the horizon and that of the smoke body itself both change in the same manner, and the contrast between the smoke and its haze background is independent, as will be shown, of the position of the sun.

Figure 3 gives the relative brightness of different points on the horizon as a function of their angular distances from the sun. This curve also represents the manner in which brightness of the smoke body and brightness of the haze between the observer and some point of the landscape vary with the position of the sun.

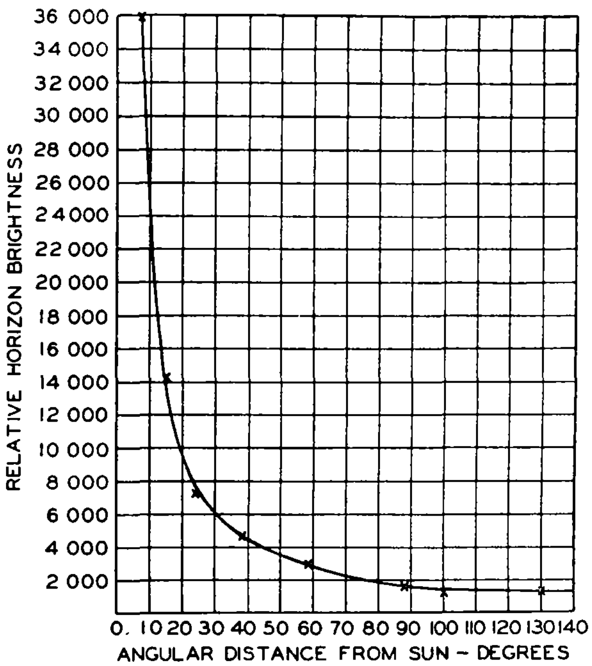

FIGURE 3.—Relation between brightness of points on the sky at the horizon and their angular distance from the sun. (Brightness of old-growth Douglas fir foliage taken arbitrarily as 100.)

Table 1 gives the relative brightness of different kinds of vegetation constituting backgrounds. The brightness of old growth Douglas fir was arbitrarily given a value of 100 and was taken as a standard for brightness measurements of other vegetation covers as well as for the horizon and haze.

TABLE 1.—*Relative brightness of different types of backgrounds*

Background type	Relative brightness
Old growth Douglas fir (used as brightness standard)	100
Ponderosa pine	140
Young Douglas fir	190
Cedar	195
Lodgepole pine	210
Bare hillsides	210
Light green brush	270–400
Bracken fern (dry)	270
Bracken fern (green)	360
Vine maple (green)	310
Vine maple (red and yellow)	470
Gray snags	690
Yellow green field grass	800

The total background brightness at the maximum safe visibility distance of the smoke column may be expressed as a function of that distance; that is, in order for the smoke to be safely visible, the maximum value that the background brightness can have is determined by the distance of the background from the observer. The complete visibility equation is

$$R(1-\rho^x)+B\rho^x=Rf(x), \qquad (1)$$

where x is the visibility distance of the smoke, R is the horizon brightness (figure 3), ρ the transmission factor (percent of light transmitted per mile), and B the background brightness, various values for which are given in table 1. The left member of equation (1) is the sum of the haze brightness, $R\ (1-\rho^x)$, and the intrinsic background brightness $B\rho^x$. The function, $f(x)$, is given in figure 2. This equation is true only when the background can be assumed to be at the same distance as the smoke.

If e^{-k} (k is the optical density) is substituted for ρ, equation (1) may be written in the form

$$kx-\log\left(1-\frac{B}{R}\right)+\log\ [1-f(x)]=0, \qquad (2)$$

which can be readily solved by the nomographic chart [3] in figure 4. To make the chart direct reading, the line representing the atmospheric variable was calibrated in distances of photometric balance of the haze meter instead of the optical density k. These two variables are related by the equation

$$e^{-kd}=0.40,$$

where d is the distance of photometric balance.[4]

Table 2 gives the results of three different measurements of the visibility distances of the test smokes against light backgrounds and also simultaneous measurements of factors affecting the visibility distance. In this table d is the distance of photometric balance against dark backgrounds; x_1 is the observed visibility distance of the smoke column; x_2 is the theoretical visibility distance given by equation (2); x_3 is the distance an observer should see the test smoke against a dark background with the values of R and d remaining constant; ρ is the transmission factor.

TABLE 2.—*Visibility distance of smokes against light backgrounds*

Test no.	d	x_1	x_2	R	B	B/R	x_3	ρ (per-cent per mile)
1	3.8	1.8	2.5	1,300	890	.685	5.8	78.5
2	5.5	6.1	6.0	1,300	370	.285	7.8	84.5
3	2.3	2.8	3.5	1,250	370	.295	4.3	67.0

The effect of color differences in the background was neglected in this study. The visibility of the smoke might be increased somewhat if the background were of a different color from the smoke body itself. Table 2 does not indicate this, although the backgrounds were light green and yellow. However, in a larger number of measurements the theoretical distance given by equation (2) would probably be slightly less than the measured distance. The color difference is usually slight since most of the background is composed of haze which has about the same color as the smoke itself. It has been the writer's experience that the visibility distance of the smoke is determined

[3] The theory and construction of nomographic charts may be found in "Design of Diagrams for Engineering Formulas", by Hewes and Seward.

[4] For the sake of uniformity all air transparency measurements in this study were made against dark backgrounds, although measurements of the visibility distances of test smokes were made against both light and dark backgrounds. If air transparency measurements are made against light backgrounds whose brightness cannot be neglected, the optical density k, and the distance of photometric balance are related by the equation

$$kd'+\log\left(\frac{0.40}{1-B/R}\right)=0.$$

To use the d' in this equation as the atmospheric variable, it would be necessary to solve for k and substitute this value in equation (2) and prepare a new chart.

more by its brightness contrast with its background than by color contrast. This seems to be especially true when the boundary between the smoke and its background is not well defined.

Curve B in figures 5 and 6 was constructed by means of the nomographic chart (fig. 4) from the data given in table 1 and figure 3. The radii of the curves designated B in figures 5 and 6 represent the visibility distances of small smokes in the sunlight as seen from the observation point O. Since these curves are nearly circular, to construct them it is necessary to find only their maximum radii toward and away from the sun (from their displaced center). Table 3 gives several pairs of these maximum radii of curve B for different times and conditions.

From figures 5 and 6 or table 3 it can be seen that the visibility distance of small smoke columns is greatest at small angular distances from the sun, that is, when the observer faces the sun. This finding is contradictory to the opinion formerly held by nearly all foresters, but it has been confirmed by a statistical analysis of fire records shown in table 4 which indicates that forest-fire lookouts do discover more fires in the sector facing the sun than they do in the sector away from the sun.

It can be shown from theoretical considerations that the visibility distance of smoke bodies should be greatest at small angular distances from the sun. In figure 7 an observer at O is at a distance x from a smoke body which is seen against a background of brightness B. The contrast C between the smoke and the background against which it is seen is given by the equation

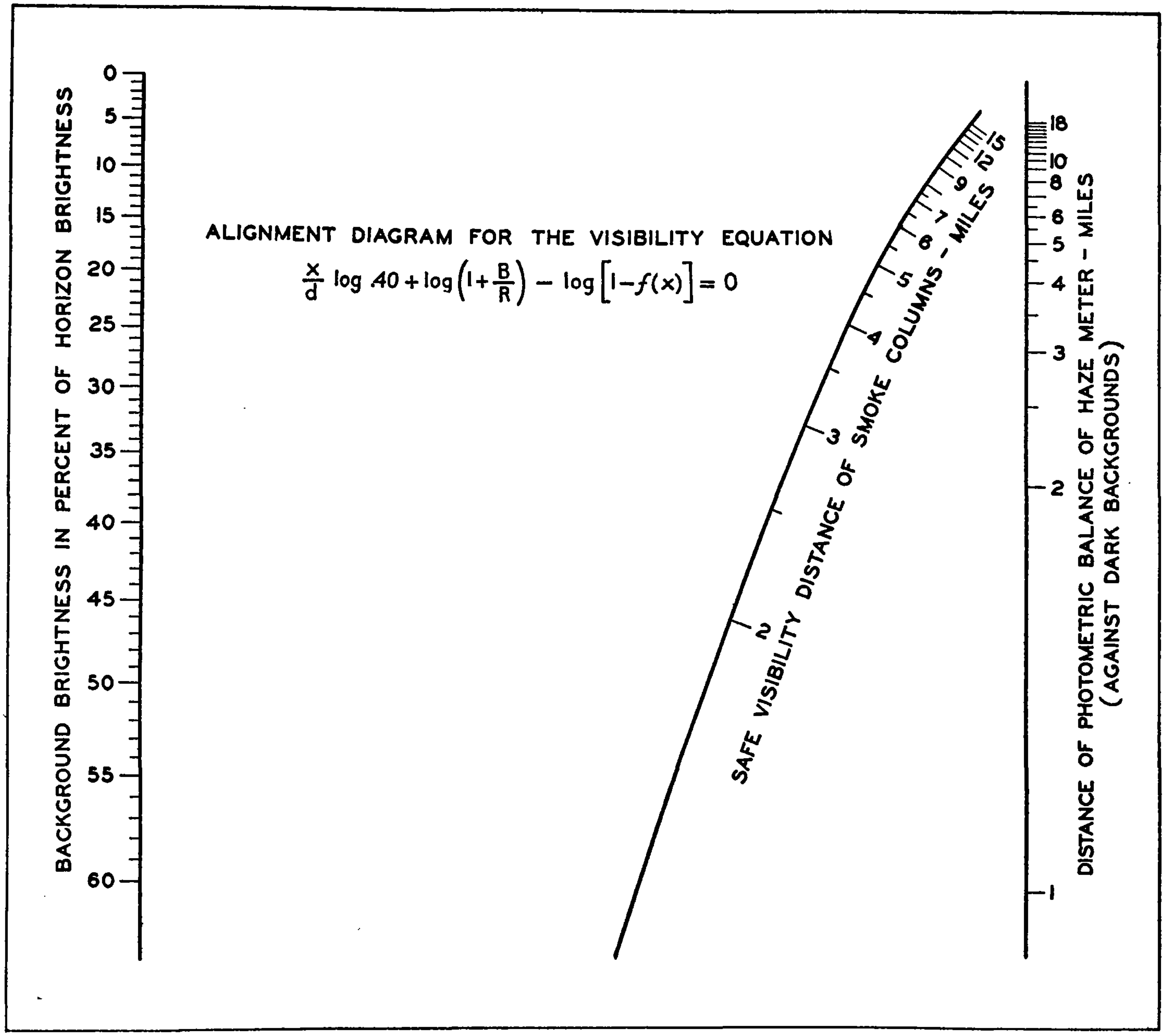

FIGURE 4.—Solutions of the visibility equation are found from this chart by connecting, with a straightedge, a point on the line representing the distance of photometric balance of the haze meter to a point on the line representing background brightness. The intersection of this line with the middle curve gives the visibility distance of the smoke column.

$$C=\frac{B_s-B_b+B_a}{B_s+B_h+B_a}, \tag{3}$$

where B_s is the average apparent brightness of the smoke body seen from O; B_b is the apparent brightness of the

TABLE 3.—*Pairs of maximum radii of safe visibility toward the sun and away from the sun, May 21 to July 21. Latitude 45° N. (B is the relative intrinsic brightness of the background, table 1, against which the smoke is seen;* d *is the distance of photometric balance of the haze meter;* x_1 *is the maximum safe radius of visibility in the direction of the sun;* x_2 *is the maximum safe radius of visibility away from the sun)*

LATITUDE 45° N.

Time of day			12:00	11:00	10:00	9:00	8:00	7:00	6:00	5:00
Time of day {a. m. / p. m.			12:00 12:00	11:00 1:00	10:00 2:00	9:00 3:00	8:00 4:00	7:00 5:00	6:00 6:00	5:00 7:00
Sun's altitude / Sun's azimuth			67° 0°	63° 32°	56° 55°	47° 74°	37° 85°	26° 96°	16° 106°	6° 115°
Background brightness	Atmospheric conditions									
B=120, yellow pine and Douglas fir	d=18 miles (clear day)	x_1 x_2	14.5 14.0	14.6 14.0	14.6 14.0	14.7 13.9	14.7 13.9	14.8 13.8	14.9 13.8	15.0 13.8
	d=12 miles (hazy day)	x_1 x_2	11.2 10.7	11.2 10.7	11.2 10.7	11.3 10.6	11.4 10.6	11.4 10.6	11.4 10.6	11.5 10.6
B=300, vine maple, bracken fern, and light brush	d=18 miles (clear day)	x_1 x_2	13.9 12.4	13.9 12.2	14.1 12.0	14.1 11.7	14.3 11.7	14.5 11.6	14.7 11.6	14.9 11.6
	d=12 miles (hazy day)	x_1 x_2	10.5 9.4	10.6 9.4	10.7 9.3	10.9 9.2	11.1 9.1	11.2 9.0	11.4 9.0	11.5 9.0
B=500, snag areas and dry grass lands	d=18 miles (clear day)	x_1 x_2	12.7 10.0	12.9 9.8	13.3 9.5	13.6 9.2	13.9 9.2	14.3 8.9	14.7 8.9	14.9 8.9
	d=12 miles (hazy day)	x_1 x_2	9.7 7.8	9.9 7.7	10.1 7.6	10.4 7.4	10.7 7.3	11.0 7.2	11.3 7.1	11.5 7.1

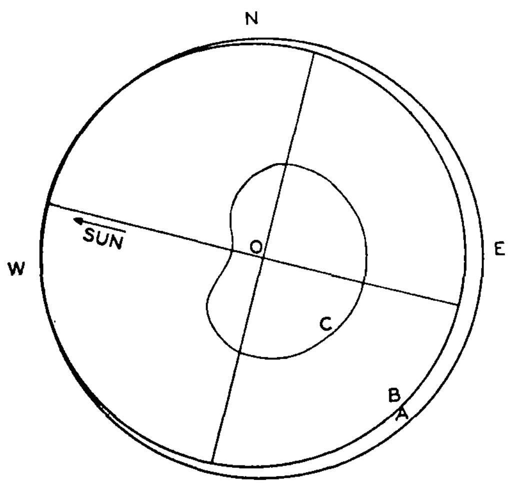

FIGURE 5.—Visibility curves on a clear day (distance of photometric balance, 18 miles) from observation point *O* for backgrounds of Douglas fir for 6 p. m. June 21, altitude of sun 16°, azimuth of sun 106° (measured from the south). Radii for curve *A* represent visibility distances of small smokes on a cloudy day; curve *B*, on a cloudless day; and curve *C*, smokes in shadow on a cloudless day.

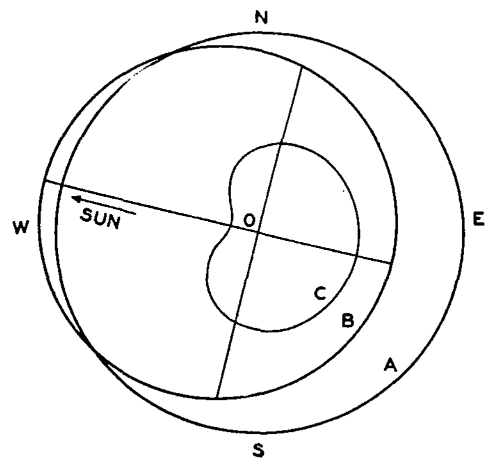

FIGURE 6.—Visibility curves on a clear day (distance of photometric balance, 18 miles) from observation point *O* for backgrounds of dry grass or snags for 6 p. m. June 21, altitude of sun 16°, azimuth of sun 106°. Radii for curve *A* represent visibility distances of small smokes on a cloudy day; curve *B*, on a cloudless day; and curve *C*, smokes in shadow on a cloudless day.

background against which the smoke is seen; B_a is the average apparent brightness of this background seen through the smoke itself; B_h is the brightness of the haze between the observer and the smoke. B_s is defined by the equation

$$B_s=\frac{e^{-kx}}{\psi}\int_\psi\int_0^l He^{-\int_0^u k_s du}\,du\,d\psi$$

where k is the optical density of the air outside the smoke body, x is its distance from the observer, ψ is the solid angle it subtends at the observer's eye, l is its diameter at any point in the direction of x, and u is the distance in the direction of x of a small volume element of the smoke body measured from that part of the surface of the smoke which is visible from O. The variable H represents the amount of light scattered per unit distance inside the smoke body, and is a function of u and ψ as well as the position of the light sources illuminating the smoke. The optical density k_s inside the smoke body is also a function of u and ψ.

B_b is given by the equation

$$B_b=B_e^{-kx},$$

where B is the intrinsic brightness of the smoke's background.

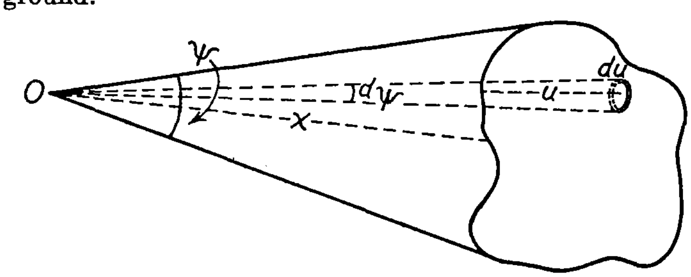

FIGURE 7.

B_a is given by the equation

$$B_a=\frac{Be^{-kx}}{\psi}\int_\psi e^{-\int_0^l k_s du}\,d\psi$$

The haze brightness B_h is given by the equation

$$B_h = R(1 - e^{-kx}),$$

where R (fig. 3) is the horizon brightness in the direction of x.

Table 4.—*Effect of sun position on the discovery of fires by lookouts Based on all the lookout-discovered fires in the national forests of Oregon and Washington over a 4-year period*

Altitude of sun in degrees	180° sector toward sun			180° sector away from sun			360° around lookout	
	Number of fires discovered		Average discovery distance	Number of fires discovered		Average discovery distance	Total fires discovered	
	Number	*Percent*	*Miles*	*Number*	*Percent*	*Miles*	*Number*	*Percent*
0°–29°	507	62	8.8	306	38	7.5	813	100
30°–44°	401	63	9.5	235	37	8.5	636	100
45°+	768	64	9.6	430	36	9.3	1,198	100
All angles combined	1,676	63	9.3	971	37	8.5	2,647	

Since the values of R and also H increase with decreasing values of θ, the angular distance of the smoke body from the sun, the contrast C will increase with decreasing values of θ, because the terms B_s and B_h increase in the same proportion, and the terms B_b and B_a remain constant; hence the visibility distance of smoke bodies is greatest when they are observed at small angular distances from the sun. However, it is advisable for an observer to wear smoked glasses when looking into a low sun, since Fechner's psychophysical law[5] breaks down under strong light intensities.

Objects such as trees and houses cannot be seen as far in the direction of a low sun as in the direction away from the sun. If the transmission factor remains constant, a decrease in the visibility distance of these objects indicates an increase in the visibility distance of smoke bodies and could be used as a rough method for estimating visibility conditions for smoke bodies.

Toward the sun, in early morning and late afternoon, in mountainous country, a large part of the visible land surface is in shadow. The range of visibility for smoke columns in shadow can be deduced from theoretical considerations as follows: The ratio of the brightness of the haze, at the distance of maximum visibility, to the apparent brightness of the smoke body must be equal to the same function of x that is used in deriving equation (2). The brightness of the haze background is $R(1-\rho^x)$, and the apparent brightness of the smoke is $R(1-\rho^x)+K\rho^x$, where K is the brightness of the smoke body itself:

$$\frac{R(1-\rho^x)}{R(1-\rho^x)+K\rho^x} = f(x). \tag{4}$$

This equation may be written

$$\frac{Kf(x)}{R[1-f(x)]} = e^{kx} - 1. \tag{5}$$

Since the value of kx is usually small, equation (5) may be written approximately

$$kx - \frac{Kf(x)}{R[1-f(x)]} = 0, \tag{6}$$

[5] Helmholtz, Physiological Optics, vol. II, pp. 172–181.

which can be solved by nomographic chart methods. The numerical value of K is 240.

The small heart-shaped curves (designated C) in figures 5 and 6 represent the theoretical visibility distances of smoke columns in shadow, as computed from equation (6). Full experimental proof of the accuracy of these curves is not yet available because only a few tests have been made with the smokes in shadows; hence they should not be considered as reliable as the curves for the range of visibility for smoke columns in full sunlight, which are based on a large number of actual tests.

Equation (6) does not hold for days when the smoke layer over a given region is rather dense and fairly deep, because the oblique rays coming from a low sun may be almost completely absorbed before reaching the earth and will have little effect in casting deep shadows. A test smoke in one of these shadows could be seen at a much greater distance than in the shadows resulting from the usual strong sunlight. If the sun is completely blotted out, the test smoke is illuminated almost entirely by light from the sky, and its visibility distance curve is the same as that for a cloudy day. Conditions like this, however, constitute only a small fraction of the usual smoky weather.

The curves A in figures 5 and 6 represent the visibility distances of small smoke columns on cloudy days. It will be noticed that they are larger than on cloudless days, especially on light backgrounds. This is due to the fact that the equivalent point source of light which would be equal to the illumination of the whole cloudy sky in its lighting effect on a smoke body would not be situated at the zenith but at a point infinitely far away, about 50° from the smoke body. If the sky is uniformly clouded over it may be regarded as a hemisphere of infinite radius and the angular position of the equivalent point source may be determined by the equation

$$f(\theta)_{\text{eff.}} = \frac{1}{2}\int_0^{\pi} f(\theta) \sin\theta d\theta, \tag{7}$$

where θ is the angle between the direction of the smoke body and a circular ring on the hemisphere formed by the intersection of the hemisphere and a plane perpendicular to the direction of the smoke from the observer; $f(\theta)$ is the function given in figure 3; $f(\theta)_{\text{eff.}}$ is the effective value of this function for the equivalent point source. The angular position of this source corresponding to $f(\theta)_{\text{eff.}}$ given by equation (3) is about 50°. This would be the same as looking into a rather low sun, and the visibility distance of the smoke body would be somewhat greater than the average distance for a cloudless day. It can also be shown that one-half of the brightness of the smoke is contributed by the small section of the clouded sky behind the smoke which has an area of only one-seventh the area of the whole clouded sky. Measurements of the ratio of the vegetation brightness and the horizon brightness on a cloudy day give the same ratio that is obtained on a clear day from measurements of the vegetation brightness and the horizon brightness at a point 50° from the sun.

Although the curves for the visibility distances of smoke bodies in figures 5 and 6 are based on the standard smoke test curve (fig. 1), the radii of these curves may be interpreted as being distances of approximately equal visibility for smokes larger than the small standard smokes. This last interpretation might be more useful since it would not connect visibility conditions with any given size of smoke volume.

The visibility distance of a smoke body having a mean diameter D times that of the standard test smoke may be found by writing the visibility equation in the form

$$\frac{x}{d}\log 40+\log (1-B/R)-\log\left[1-f\left(\frac{x}{D}\right)\right]=0,$$

where x is the visibility distance and d the distance of photometric balance. A few solutions of this equation for x (for dark backgrounds) with different values of D are given in table 5.

TABLE 5

d (Distance of photometric balance in miles)	x (Visibility distance in miles)			
	$D=1$	$D=4$	$D=6$	$D=8$
8	8.6	13.2	14.8	15.8
12	11.5	16.2	19.8	21.6
16	14.0	21.4	24.4	26.3

If a standard size of test smoke is observed through binoculars, D becomes the magnification (in diameters) of the binoculars.

It can be shown that the small test smoke might be visible at a distance of 65 or 70 miles if the transmission factor were 100 percent. However, this can never happen, because even on the clearest days each mile of the lower atmosphere absorbs and scatters 3 or 4 percent of the light traveling through it. Thus, the haze resulting from this scattering, as well as the decrease in the smoke's actual brightness, causes a tremendous loss in visibility distance, even under the most favorable conditions.

CONCLUSIONS

1. Small smoke columns can be seen farther when the observer is looking into a low sun than when the observer has the sun at his back. Trees, houses, and similar objects cannot be seen as far toward a low sun as they can away from the sun.
2. The locus of the position of a smoke column in sunlight at the maximum distance of visibility from an observation point is approximately a circle. The observation point is displaced from the center for light backgrounds, but moves nearer the center for dark backgrounds. The radii of such curves increase as the brightness of the background decreases.
3. The visibility distance does not change greatly with intrinsic background brightness in the direction of a low sun, because the haze in that direction is always many times brighter than any natural background.
4. From indirect measurements and theoretical considerations it appears that smoke columns can be seen farther on cloudy days than on clear days, the difference being much greater against light backgrounds than against dark backgrounds. Opaque objects such as trees cannot be seen as far on cloudy days as on cloudless days.
5. For all practical considerations, the safe visibility distance of smoke columns in shadows appears to be zero in the direction of a low sun.
6. Small changes in the size of a smoke body do not cause appreciable changes in its visibility distance.
7. In very clear weather small changes in atmospheric conditions will result in large changes in visibility distance.

DESTRUCTIVE EASTERLY GALES IN THE COLUMBIA RIVER GORGE, DECEMBER 1935

By D. C. CAMERON and ARCHER B. CARPENTER

[Weather Bureau, Portland, Oreg., August 1936]

Several times each winter the easterly winds in the Columbia River Gorge reach gale force, and continue at that velocity for a week or 10 days, and in some instances for nearly a month (1) (2). In December 1935 the easterly winds reached such a force that all wind instruments at Crown Point, Oreg., were completely carried away.

This tremendous flow of air is a result of deepening of nocturnally cooled air collected over the Columbia and Snake River Basins, which, like the water in these rivers, finds its way out through the Columbia River Gorge, a natural water-level route through the Cascade Range.

Any cessation of cyclonic activity in this large inland basin permits rapid cooling, by nocturnal radiation, of the polar Pacific air which normally is present. This cooling soon builds up a deep, cold layer, filled with low stratus clouds and fog; and the air flow westward through the gorge increases in proportion to the depth of the cold air (3) (4). Occasionally a small amount of transitional polar continental (N_{PC}) air which has spilled westward through the passes in the Rocky Mountains adds to this drainage. When this occurs a drop is noticed in the temperature and dew points in the gorge, and an increase is noted in the wind velocities. Such a combination of air drainage was sufficient on December 20, 1935, to cause considerable destruction at Crown Point, Oreg., and elsewhere in the western gorge area.

The ratio between the pressure gradient from Hood River to Portland, Oreg., and the easterly winds at Cascade locks and Crown Point is quite constant, as may be seen from figure 1. The top and bottom curves on the graph represent *easterly* wind velocities *above* the neutral lines, and *westerly* wind velocities *below*. The upper and lower curves are for Crown Point and Cascade locks, respectively. The center curve represents difference in pressure from Hood River to Portland, with plus values when the pressure gradient was directed from Hood River toward Portland, and minus values when the reverse occurred.

Pilots using this airway estimated wind velocities at 4,000 feet to be about 30 miles per hour when the surface velocities averaged about 50 miles per hour. The pilots did not fly in this air stream, as it was extremely turbulent; the estimate was based on the very rapid rate at which clouds, from the upper portion of the inland lake of cold air just below the inversion, were flowing westward over a 4,000-foot ridge. The pilots flying this route were amazed as they watched these clouds being carried violently into the gorge and dissipated. The top of the stratus clouds east of the Cascade Range was reported at a maximum of approximately 5,000 feet. This maximum was reached after the addition of the N_{PC} air. The previous top was usually between 3,300 and 4,500 feet.

Lowering of the cold air top east of the Cascade Range was partly counteracted by radiation cooling at the top of the cloud layer in the cold air, and by radiation cooling on the mountain slopes rising above the lake of cold air. Small additions of N_{PC} air coming westward through the passes in the Rocky Mountains temporarily increased the depth of the cold air, and increased the flow through the gorge.